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DEPARTMENT OF PHYSICS

SRCC REPORT NO. 126

NGL-39-011-002

UNIVERSITY OF PITTSBURGH
PITTSBURGH, PENNSYLVANIA

4 JUNE 1970

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The Center is supported by an Institutional Grant ~~(NsG-416)~~ from the National Aeronautics and Space Administration, strongly supplemented by grants from the A. W. Mellon Educational and Charitable Trust, the Maurice Falk Medical Fund, the Richard King Mellon Foundation and the Sarah Mellon Scaife Foundation. Much of the work described in SRCC reports is financed by other grants, made to individual faculty members.

THE POLARIZATION OF LYMAN ALPHA RADIATION PRODUCED BY DIRECT EXCITATION OF HYDROGEN ATOMS BY PROTON IMPACT†

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ABSTRACT

The polarization of Lyman alpha radiation resulting from the direct excitation of hydrogen atoms by proton impact has been measured in the energy range from 2 to 21 keV. A Brewster's angle polarization analyzer was used to measure the polarization of the observed Lyman alpha radiation. The results are compared with the 4-state Sturmian calculation of Gallaher and Wilets.

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†This research was supported in part by the National Science Foundation.

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INTRODUCTION

A very sensitive test of the validity of various approximations used in collision theory can be obtained by comparing the polarization of radiation measured in collision experiments with theoretically calculated values. In addition, knowledge of the polarization of collisionally induced radiation is needed when making cross section measurements, where a detection system observes radiation emitted normal to a plane containing two interacting crossed beams, because the total cross section Q_T can only be obtained by using the expression

$$Q_T = Q_{90} \, (1 - P/3) \tag{1}$$

where Q_{90} is the apparent cross section that is measured, assuming an isotropic distribution of the emitted radiation, and P is the polarization of the emitted radiation. The polarization is defined as

$$P = \frac{I_{\parallel} - I_{\perp}}{I_{\parallel} + I_{\perp}} \tag{2}$$

where $I_{\parallel}$ and $I_{\perp}$ are the intensities of the components of radiation (observed at an angle of 90° with respect to the plane containing the crossed beams), with their electric vectors oscillating parallel and perpendicular, respectively, to the direction of the exciting particle beam. In this paper we are concerned with measuring the polarization of the Lyman alpha radiation produced by direct excitation of hydrogen atoms by proton impact.

The cross sections for the production of Lyman alpha radiation in collisions between energetic protons and hydrogen atoms by the processes

$$H^+ + H \rightarrow H^+ + H(2P) \qquad \text{Direct excitation, and} \tag{3}$$

$$H^+ + H \rightarrow H(2P) + H^+ \qquad \text{Charge transfer}$$

have been measured by Stebbings et al.[1] They did not measure the polarization of the emitted Lyman alpha radiation, and in order to obtain total cross section values from their measurements they relied on a Born approximation model calculation by Fennema[2] which predicted a slowly and monotonically decreasing value for the polarization as a function of the proton energy. This polarization correction was always less than 10% and had little effect on the general shape of their total cross section curve.

More recent calculations of the polarization of Lyman alpha radiation produced in proton-hydrogen atom collisions have been made by Wilets and Gallaher using a 4-state hydrogenic wave function expansion[3] and a 4-state Sturmian expansion.[4] Both of their calculations predict polarizations which are rapidly varying as a function of proton energy below 25 keV.

An angular distribution technique has been used to measure the polarization of Lyman alpha radiation produced in He^+ + H collisions[5] and in proton-inert gas collisions,[6] but it is nearly impossible to use this technique for H^+ + H collisions due to the ambiguity which is introduced by the two separate processes for populating the 2P state. However, the development of the Brewster's angle reflection technique in this laboratory[7] has enabled us to measure the polarization of the directly-excited Lyman alpha radiation after the radiation from the charge transfer reaction has been filtered out in the detection system.

EXPERIMENTAL APPROACH

The basic experimental apparatus is shown in Fig. 1. The source of the atomic hydrogen beam was a heated tungsten furnace (2700°K) located in the first of three differentially-pumped vacuum chambers. In the intermediate chamber the atomic beam was modulated at 270 Hz by a rotating toothed chopper wheel. The modulated beam then passed into the third chamber where it was crossed by a proton beam. Downstream along the hydrogen beam was a quadrupole mass analyzer which was used to determine the relative content of hydrogen atoms and molecules in the beam.

The proton beam was produced in a fourth vacuum chamber which was attached to the third chamber. An electron bombardment ion source was used to produce hydrogenic ions which were accelerated and focused into a beam. This ion beam was then shaped by a quadrupole lens pair and analyzed by a 90° sector magnetic field. After entering the third chamber the proton beam was aligned and focused so that it would pass through the hydrogen beam. Assurance that the ion beam passed through the atom beam was achieved by using two concentric proton collectors. A deep Faraday cup served as a central collector which collected only protons passing through the atom beam while the remainder of the protons were collected by an outer collector. The possible emission of secondary electrons from the central collector was investigated by biasing it with respect to the outer collector and monitoring the current; it was determined that this was no problem and the central collector was normally grounded through the current measuring electrometer while the outer collector was directly grounded. For normal operating conditions more than 99% of the proton beam was collected by the central collector with the beam currents ranging from 1×10^{-8} A at the lowest energy to 3×10^{-7} A at and above 10 keV.

A schematic of the polarization analyzer and detection system is shown in Fig. 2. The polarization analyzer consisted of a crystal of lithium fluoride set at the Brewster's angle for incident Lyman alpha radiation from the beam interaction region. Only the component of incident radiation with its electric field vector oscillating parallel to the crystal surface is reflected into the Lyman alpha detector, an iodine-vapor-filled uv photon counter[8] preceded by an absorption filter of molecular oxygen. By rotating the analyzer-detector assembly 90° about an axis coincident with the collimated radiation incident on the analyzer, it was possible to measure directly the intensities of the two orthogonal components of the incoming radiation, I_P and I_S, whose electric vectors oscillate parallel and perpendicular, respectively, to the plane containing the proton beam and the propagation vector of the incident radiation.

Several precautions were taken to ensure that only the desired Lyman alpha radiation was being observed: The photon counter was shielded so that only radiation reflected from the analyzing crystal could be detected. The nearest surface from which reflected uv radiation could be incident on the analyzer was 30 cm away and coated with colloidal graphite, while the interaction volume of the beams was only 6 cm from the analyzer; therefore, it was believed that reflection of uv radiation from surfaces did not affect our results. To minimize Stark quenching of metastable hydrogen atoms in the region viewed by the analyzer, all the surfaces in the vicinity of the beam interaction region were grounded to restrict penetration of electric fields. The magnetic field was also measured in this region and found to be only that of the magnetic field of the earth.

In order to distinguish the directly-excited Lyman alpha radiation from that originating from the charge transfer process, the analyzer-detector assembly was positioned to observe radiation at a non-normal angle θ with respect to the proton beam direction. Since the radiation from the charge transfer collisions is emitted by rapidly moving hydrogen atoms the wavelength of the observed radiation will be Doppler-shifted according to the expression

$$\lambda_o = \lambda_L \left(1 - \frac{v}{c} \cos\theta\right) \qquad (5)$$

where λ_o is the observed wavelength, $\lambda_L = 1216\text{Å}$, v is the velocity of the fast hydrogen atoms, and c is the speed of light. The absorption of the molecular oxygen filter is such that Lyman alpha lies near the bottom of a narrow transmission window[9,10] and, as a result, the Doppler-shifted Lyman alpha is absorbed more strongly by the filter than the Lyman alpha from the direct excitation process. The amount by which the Doppler-shifted radiation is absorbed by the filter is dependent on the length of the filter, the angle of observation, the velocity of the emitting atom, and the pressure in the filter. Since the length of the filter (1.67 cm) and the angle of observation (54.7°) were fixed in the apparatus, it was decided to adjust the pressure in the filter in order to selectively detect the directly-excited Lyman alpha radiation. The optimum oxygen pressure in the filter at each energy was determined by observing the Lyman alpha radiation emitted in proton-argon collisions where the Lyman alpha arises solely from a charge transfer process. This optimum pressure was obtained in the following manner: First, radiation was detected with the oxygen filter evacuated. Then, molecular oxygen was admitted to the filter so that about 99% of this charge transfer radiation was absorbed. With this pressure in the filter it was determined that for proton energies greater than 3 keV, the transmission of the filter for directly-excited Lyman alpha was greater than 30%. Therefore, it was concluded that less than 4% of the detected radiation from the proton-hydrogen atom collisions arose from the charge transfer process.

The polarization analyzer assembly was designed so that it could be rotated into three positions, 0°, 90°, and 180°. The 180° position is shown in Fig. 2 and was used to measure the I_S component of the incident radiation. By rotating the analyzer a quarter turn from the 180° position the I_P component of the observed radiation was determined (the 90° position). The 0° position was a half turn from the 180° position and was also used to measure the I_S component. Several signal measurements were made in each of these positions to accumulate data and it was required that the signal measured in the 0° and 180° positions agree for the data to be acceptable.

The pulse count rates, as recorded by twin scalers, were sufficiently small that the loss of counts due to the measured recovery time of the photon counter (500 microseconds) was entirely negligible.

Since the usual definition of polarization, as in Eq. (2), is made according to the components of radiation observed at 90° to the proton beam direction, it was necessary to account for the fact that the components of radiation measured in this experiment were for an observation angle of 54.7°. It can be shown that the polarization can be calculated directly from the measured radiation components, I_S and I_P, by the expression

$$P = \frac{I_P - I_S}{I_P(2E + 1)/3 + I_S(2E - 1)/3} \tag{6}$$

where E is the efficiency of the polarization analyzer which has been determined to be 0.94.[7]

It is known that, under proton bombardment, molecular hydrogen emits Lyman alpha and molecular radiation to which the oxygen-filtered detector responds.[11]

As the beam in the present experiment contained a non-negligible proportion of the molecular species it was necessary to allow for the contribution of the molecular radiation to the observed signal. The proportion of molecular hydrogen in the beam was determined with the quadrupole mass filter. Under conditions of effusive flow from the source, the molecular signal S should be inversely proportional to the square root of the source temperature, that is,

$$ST^{1/2} = \text{constant}. \tag{7}$$

This condition was verified by measuring I_P and I_S with the source at room temperature and again with the source at approximately 1500°K where the temperature was measured with an optical pyrometer by viewing the furnace aperture through a window located downstream from the neutral beam. The temperature of the furnace was then increased to approximately 2700°K where the beam was mainly atomic. Here the molecular hydrogen contribution to the signal was

$$I_{H_2} = S_R \ (T_R/T)^{1/2} \ (1 - D) \tag{8}$$

where S_R was the signal recorded at room temperature, T_R, and D was the measured dissociation of the hydrogen beam at the normal operating temperature T = 2700°K. In the present experiment D was usually about 70%. Both I_P and I_S were corrected for the molecular hydrogen signal contribution before being used to calculate the polarization from Eq. (6).

The polarization of the countable uv radiation from $H^+ + H_2$ collisions was measured in the same manner as above except that the furnace was at room temperature.

RESULTS AND DISCUSSION

The experimental values for the polarization of the Lyman alpha radiation produced by direct excitation in proton-hydrogen atom collisions are shown in Fig. 3 with the error bars representing plus and minus one standard deviation from the mean values for the accumulated data. The calculation by Gallaher and Wilets using the 4-state Sturmian representation[4] is shown in Fig. 3 as a solid line. It can be seen that there is quite good agreement in magnitude between the two sets of data. Although the rather large uncertainty in the experimental data precludes an accurate comparison, the shapes are somewhat similar.

The calculation by Wilets and Gallaher using the 4-state hydrogenic wave function expansion[3] and the Born approximation model calculation by Fennema[2] are in disagreement with the present results. If the total cross section measurements by Stebbings et al[1] were corrected for polarization effects with the present results, rather than the calculation by Fennema, their total cross section curves would be altered slightly in shape and less than 10% in absolute magnitude.

The polarization of detectable radiation produced by the direct excitation of hydrogen molecules by protons is shown in Fig. 4. The error bars represent plus and minus one standard deviation of the data.

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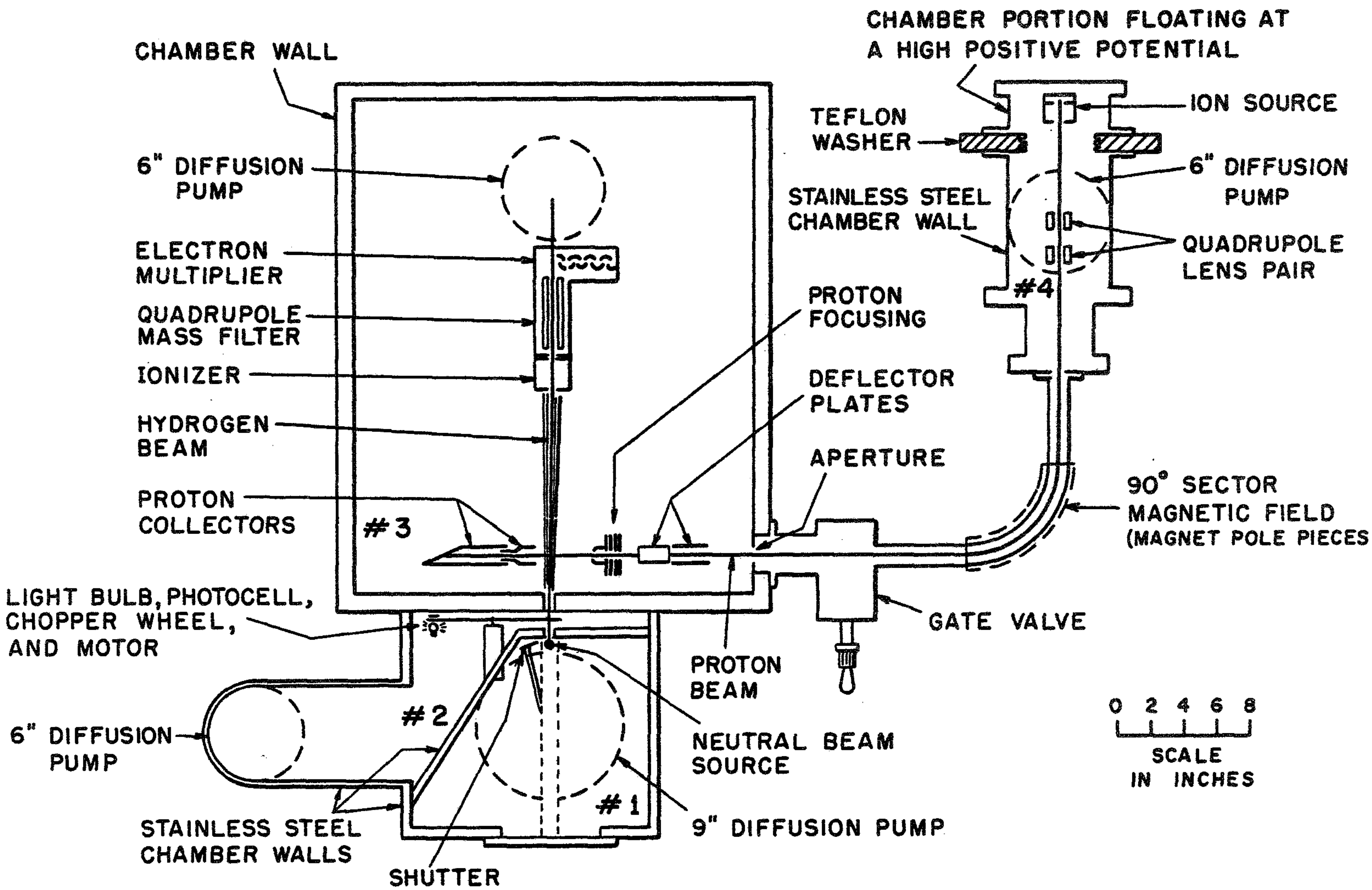
FIGURE CAPTIONS

1. Basic experimental apparatus for producing and monitoring the proton and hydrogen atom beams.
2. Schematic of the Brewster's angle polarization analyzer and the proton detection system. In the analyzer position shown, part of the radiation component I_S is reflected into the photon detection system while the I_P component is completely transmitted by the LiF analyzer. The H atom beam is perpendicular to the plane of the drawing.
3. Experimental values of the polarization of the Lyman-alpha radiation produced by direct excitation of hydrogen atoms by proton impact compared with the theoretical calculations by Gallaher and Wilets using the 4-state Sturmian representation.
4. Experimental values of the polarization of the countable uv radiation produced by direct excitation of hydrogen molecules by proton impact.



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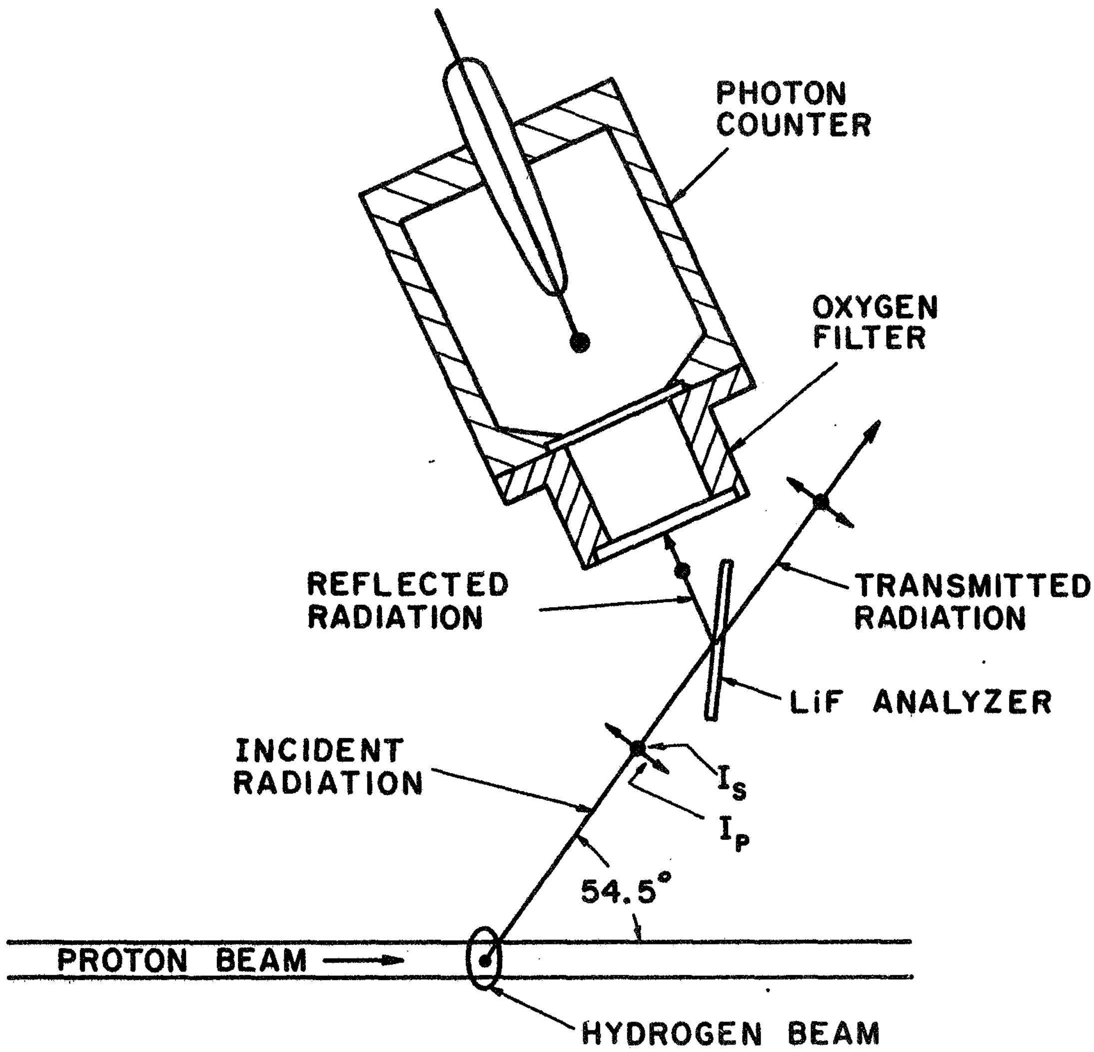

Figure 2. Schematic of the Brewster's angle polarization analyzer and the proton detection system. In the analyzer position shown, part of the radiation component I_S is reflected into the photon detection system while the I_P component is completely transmitted by the LiF analyzer. The H atom beam is perpendicular to the plane of the drawing.

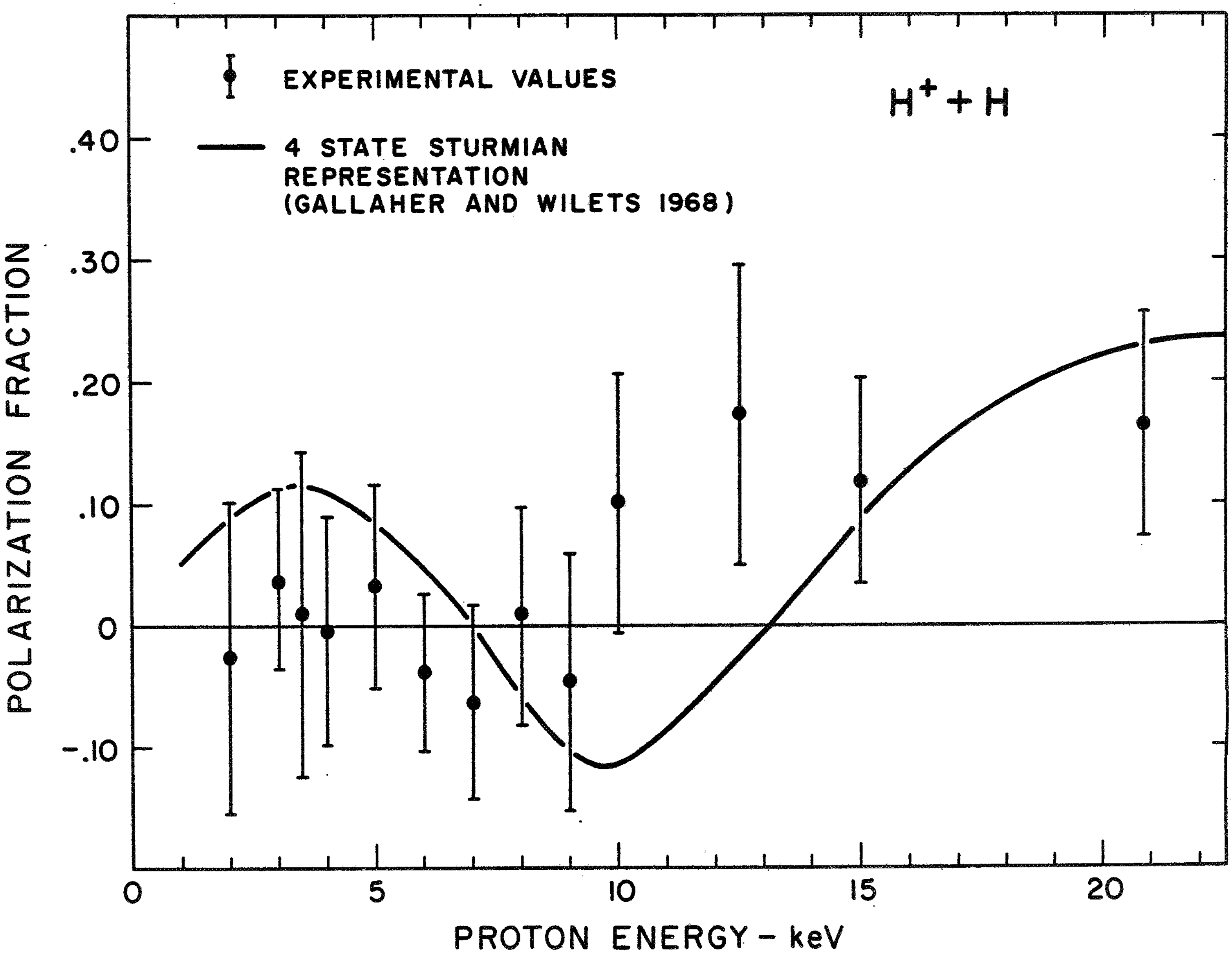

Figure 3. Experimental values of the polarization of the Lyman-alpha radiation produced by direct excitation of hydrogen atoms by proton impact compared with the theoretical calculations by Gallaher and Wilets using the 4-state Sturmian representation.

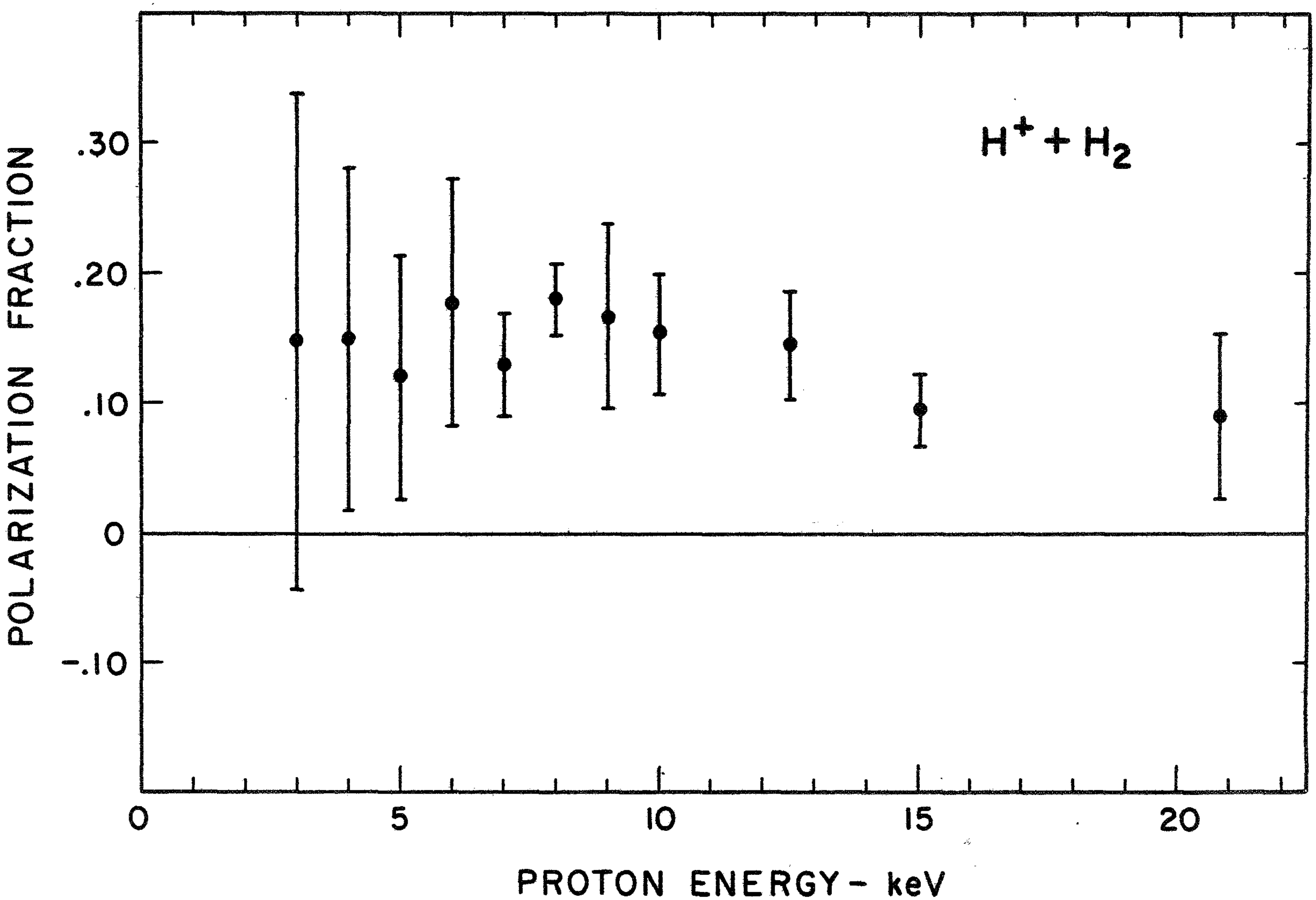

Figure 4. Experimental values of the polarization of the countable uv radiation produced by direct excitation of hydrogen molecules by proton impact.